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RECENT RESULTS OF SONIC BOOM RESEARCH

By Harvey H. Hubbard

NASA Langley Research Center  
Langley Station, Hampton, Va.

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## RECENT RESULTS OF SONIC BOOM RESEARCH

Harvey H. Hubbard  
NASA Langley Research Center  
Langley Station, Hampton, Virginia

### INTRODUCTION

This paper includes a brief state-of-the-art review of sonic boom technology. Particular emphasis is placed on the physical aspects of the problem such as the exposure pattern development, propagation through an inhomogeneous atmosphere, and the effects on structural responses. Discussion is limited to the more recent research findings.

### BASIC PHYSICAL PHENOMENA

Sonic booms associated with the shock waves of aircraft are very similar in their physical aspects to the crack of a bullet (see Ref. 1). Two relatively strong waves are associated with the bow and tail of a bullet in supersonic flight (Fig. 1). Between these waves and close to the body surface can be seen other weaker waves. At relatively larger distances, these weaker waves tend to coalesce with the stronger ones, the result being that in the distant pressure field only two main waves can be identified.

In the case of an aircraft, the presence of lifting surfaces results in flow-field asymmetry and marked variations exist in its shock wave patterns in different radial directions. If the waves generated by an aircraft could be made visible, they might appear as indicated in the sketch of Figure 2 for a particular flight condition (Ref. 2). At locations near the aircraft the flow field is closely related to the detail geometry of the aircraft and is markedly different at comparable distances above and below. The individual waves of the flow field tend to coalesce as for the bullet with the result that the pressure signature at large distances from the aircraft tends to approach an N-type pressure disturbance at the ground.

The sonic boom ground exposure patterns of an aircraft in supersonic flight are shown schematically in Figure 3 from Ref. 3. Booms are first observed at a distance of about 100 miles from take-off and the pattern terminates at about the same distance from the destination. The overpressure amplitudes are greatest on the ground track. As the aircraft altitude increases, the overpressures decrease and there is an associated widening of the exposure pattern. At the altitudes usually associated with cruise flight the N-wave type disturbance pictured schematically at the bottom of Figure 3 is usually encountered.

### INFLUENCE OF THE ATMOSPHERE

The details of the pressure signature on the ground may vary because of atmospheric effects (see Ref. 4) and also as a function of

aircraft type and operating conditions. As the size and weight of the aircraft increase, the time duration of the signatures generally increase as in reading from left to right in Figure 4. Effects of the atmosphere result in wave shape distortions. These distortions are associated mainly with the rapid compressions of the waves and are noted to be similar in nature for all of the aircraft.

Variations induced by the atmosphere are found to be statistical in nature. The data of Figure 5 relate to the overpressures from three different aircraft being operated during the same time period for comparison. The probability of equaling or exceeding given values of the ratio of measured to calculated sonic boom overpressures is given along with the associated histograms. It can be seen that the variability for the three aircraft is very much the same, thus suggesting that the size of the aircraft or length of the pressure signature is not a significant factor in the atmospheric effects problem. Greater variability may occur at points remote from the ground track or when the atmosphere is disturbed.

One of the more recent discoveries is the existence of wavelike patterns of the overpressures along the ground (Fig. 6). The measured values fluctuate above and below the expected mean value, and a definite progression can be seen from low values to high values and back to low values. Wave lengths from a few hundred feet to a few thousand feet have been observed for these disturbances along with an orderly progression of wave shape as a function of distance along the ground (Fig. 7).

Energy spectra have been computed for two widely different shaped waves and the results are shown in Figure 8. The detail features of the spectra are very similar up to about 100 Hz but notable differences occur at higher frequencies. Other results indicate a phase scrambling at the higher frequencies.

#### EFFECTS ON STRUCTURES

The sketch at the top of Figure 9 illustrates the outside and inside exposure situations for people (see Ref. 6). In the inside exposure case, the building acts as a filter which determines the nature of the exposure stimuli reaching the observer. The ingredients of the inside exposure situation are included in the chain diagram at the bottom of the figure. The sonic-boom-induced excitation of the building which causes it to vibrate may arrive either through the air or through the ground and can be observed directly by the subject. Studies of seismic motions due to sonic booms have produced the characteristic signature shape shown in Figure 10, from Ref. 7.

The solid curve represents the measured particle velocity signature and the dashed curve represents calculations by a theory which assumes a traveling air load over an elastic medium. It can be seen that the theory accounts for the maximum velocity values and hence the traveling load effect is judged to be the dominant one. Other features of the ground response signature are identifiable. For instance, the lower frequency accelerations are associated with Rayleigh waves and their frequency varies as the speed of the airplane varies. The higher frequency is related to reflections from a

subsurface layer and hence is a function of the local geology. The maximum particle velocities recorded are about 1 percent of those observed for mild earthquakes which just begin to cause superficial damage.

Sample acceleration response time history records for a residence type structure are shown in Figure 11. At the top of the figure is shown a wall response to a B-58 sonic boom input whereas the bottom trace represents the same wall responding to aircraft flyover noise. The boom response record contains low-frequency oscillations which relate to the main framing members of the building and superposed are higher frequency oscillations which relate to the wall panels. The engine noise, on the other hand, seems to excite only the higher frequency panel responses.

Peak wall accelerations, as obtained from records of the type illustrated in the top of Figure 11, are shown for a one-story residence structure in Figure 12. Data are shown for three different aircraft as a function of overpressure. Values vary from about 0.1g to about 0.7g and there is a general trend of increased acceleration level with increased sonic boom overpressure. The dominant vibration responses were in a frequency range such that similar acceleration amplitudes were measured for small and large aircraft.

Energy spectra for two different N-waves differing markedly in time duration are given in Figure 13 from Ref. 3. The relative amplitudes of the high-frequency components are approximately the same but the low-frequency amplitudes are considerably greater for the wave of longer time duration. Structural components having low vibration frequencies would probably be excited more efficiently by the wave of longer duration. On the other hand, those having relatively higher vibration frequencies would be expected to respond in a similar manner to both N-wave inputs.

The interaction of the air cavities and the structure of the building can be important in other response modes (Fig. 14). For floor vibrations it was found that a preferred phase relationship existed because of the manner in which interior wall structures were arranged. Wall panels between the vertical studs also vibrated in a preferred manner, and higher mode panel frequencies were noted to be important. The sketch on the right-hand side of Figure 14 suggests an interaction of the structure of the building and the enclosed air cavities.

#### EFFECTS ON PEOPLE

The nature of the significant acoustic and vibratory inputs to a person is illustrated in Figure 15. The top trace is a sample outside pressure exposure as measured for one particular case. The three bottom traces represent corresponding inside-exposure stimuli. The topmost of these represents the pressure variation inside the building. The audible portion of this signal has the characteristic shape of the next lower trace and is seen to be an order of magnitude lower in amplitude. It is associated with the rattling of the building structure and furnishings. The bottom trace represents the vibration of the floor that would be sensed either directly or through the furniture.

The data of Figure 16 relate to the annoyance of sonic booms, and judgments of equivalence between booms and aircraft noise are shown by the cross-hatched region (see Ref. 2). Subjective judgments were made to pairs of exposures involving sonic boom and flyover noise flights. Outdoor judgment data define the upper portion of the region and the indoor data define the lower portion. In general the indoor exposures were noted to be more annoying than the outdoor exposures. One possible factor is the adverse effect of structurally induced noise.

One source of such noise is the vibration of hanging objects such as mirrors (see Ref. 8). Wall accelerations with and without a mirror are presented in Figure 17 as a function of force input to an adjacent wall. The acceleration increases directly as the force increases for the wall alone in the range of the tests. With the mirror attached, a vibration level can be reached at which the mirror can no longer follow the motions of the wall. At this condition the mirror impacts the wall in an erratic manner and rattling is observed. This rattling phenomenon is believed to be important subjectively.

The effects of rise time on the energy spectra are shown in Figure 18 for three different waves, each having the same time duration. Shown as a solid line in the figure is the spectrum envelope for an N-wave which by definition has a zero rise time. Also shown are spectrum envelopes for waves having rise times of 0.01 and 0.1 times the time duration of the wave, respectively. As the rise time increases the relative amplitudes of the high-frequency components of the wave decrease. This result suggests that the rise time may be an important factor subjectively.

Results of subjective tests of people in a sonic boom simulator in which rise time was varied are presented in Figure 19 (from Ref. 9). Relative annoyance level is shown as a function of rise time. The stippled region represents observations for a number of observers and for a range of signature durations. It can be seen that the annoyance level decreases markedly as rise time increases.

#### CONCLUDING REMARKS

The atmosphere is noted to affect the shapes of the pressure signatures for given flight conditions, and to cause wavelike overpressure patterns to exist over the ground. Building vibration responses which involve structural-air cavity coupling are shown to be an important factor in subjective responses as is the sonic boom wave shape. Seismic responses are predictable and are a function of the aircraft operating conditions and the local geology.

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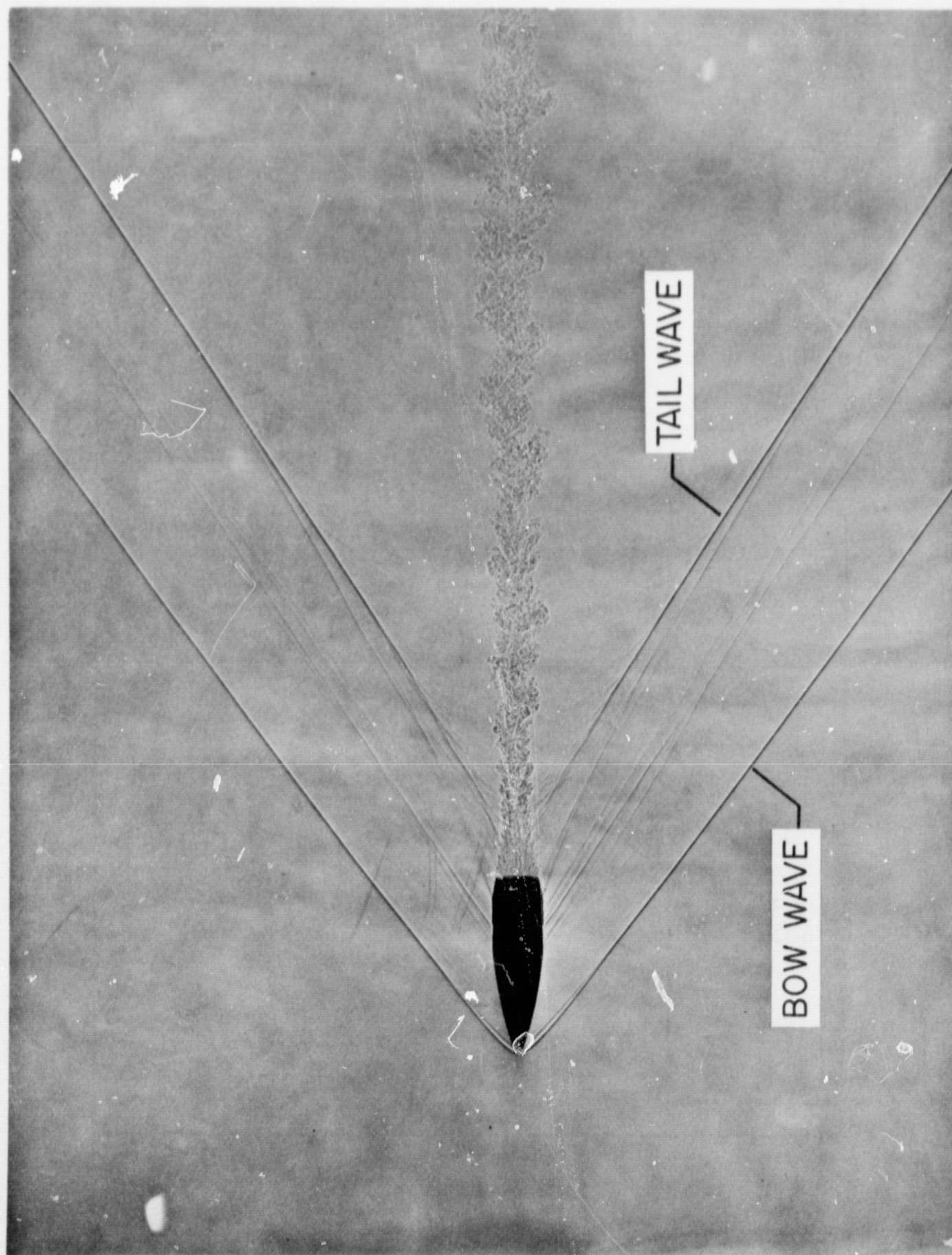


Figure 1.- Photograph of the shock wave patterns associated with a bullet in supersonic flight.  
(Data from ref. 1.)



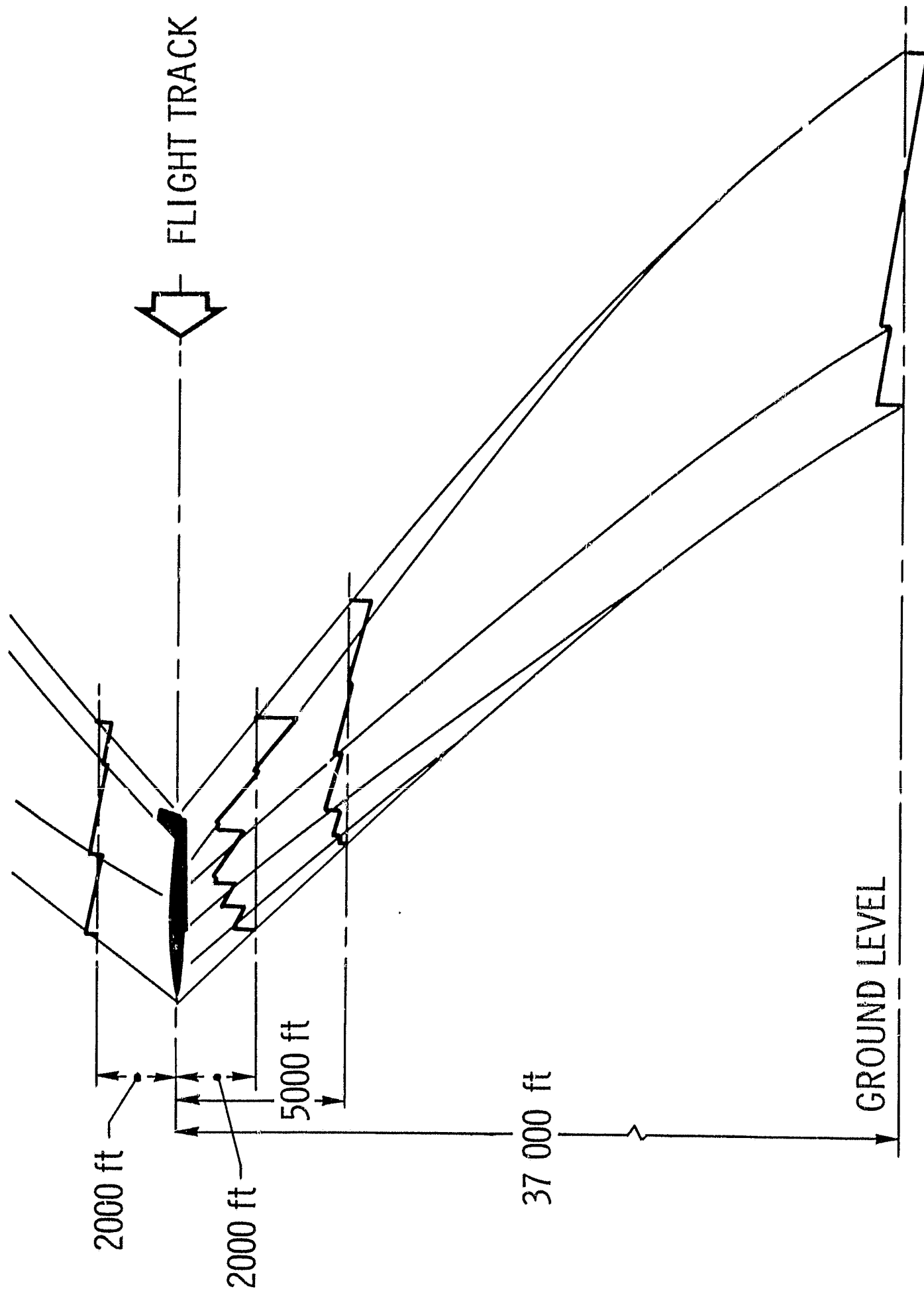


Figure 2.- Diagram showing the signatures measured in close proximity to the XB-70 aircraft in flight compared to a ground signature for the same flight conditions. (Data from ref. 2.)

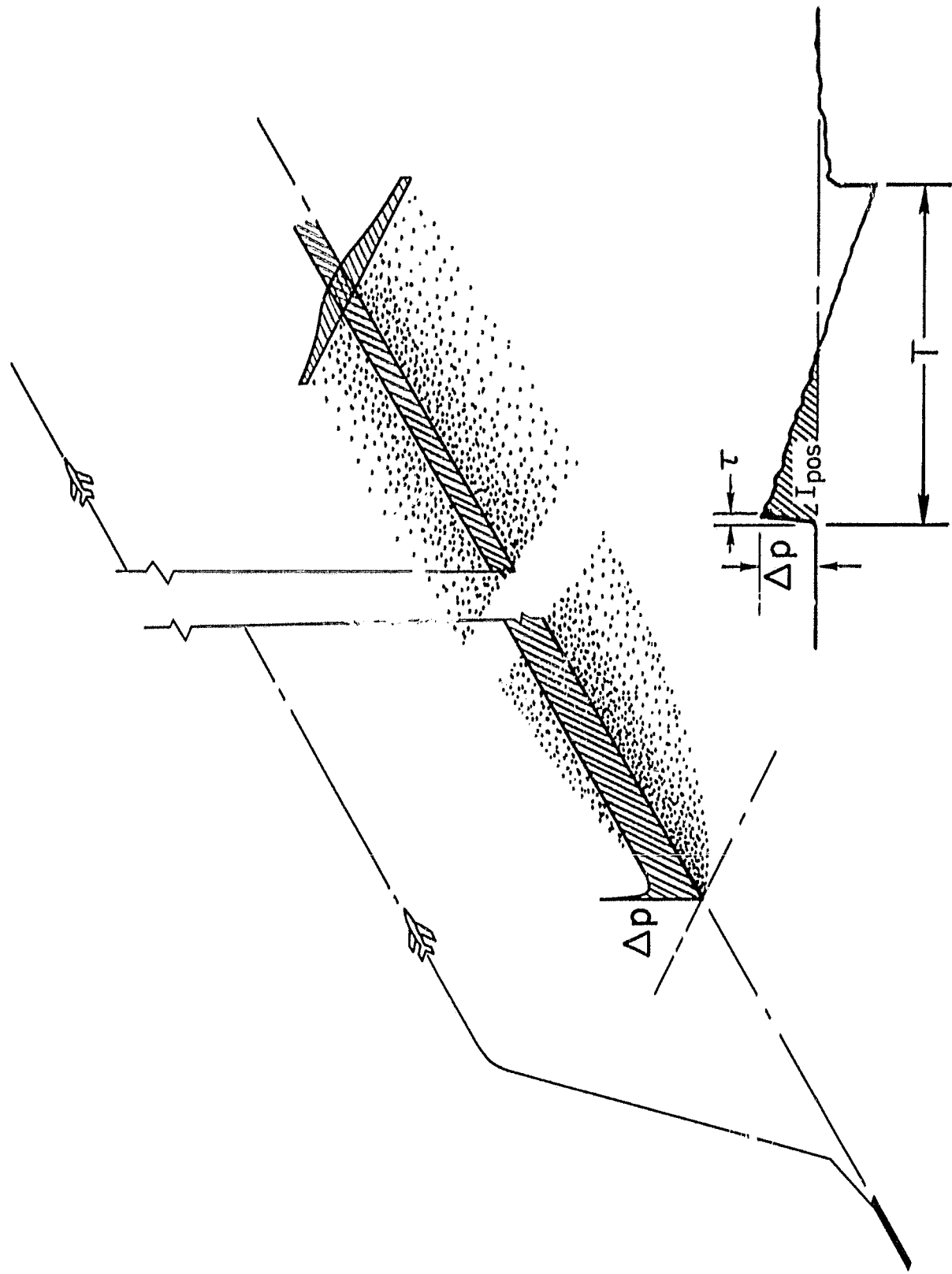


Figure 3.- Schematic illustration of sonic boom ground exposure patterns from an aircraft in supersonic flight. (Data from ref. 3.)

F-104

B-58

XB-70

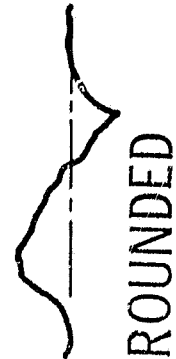
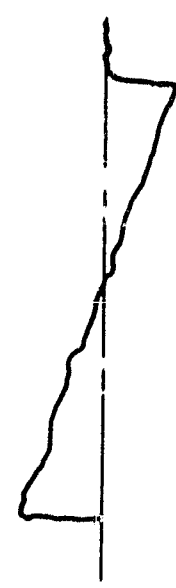
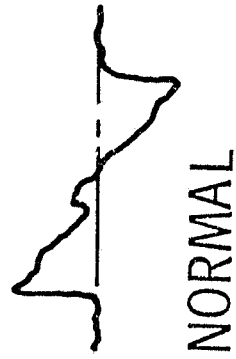
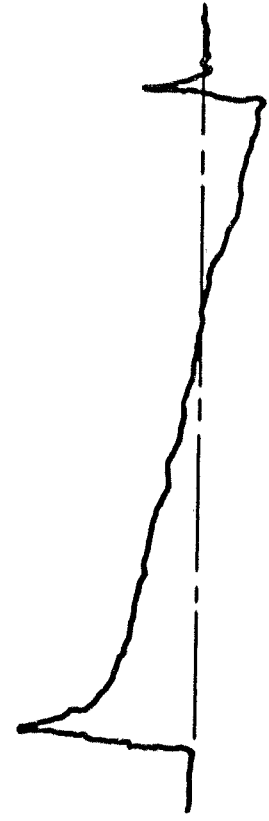
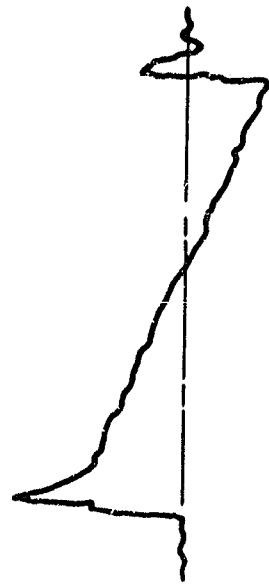
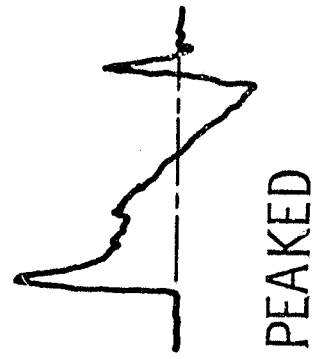


Figure 4.- Variation of measured sonic boom pressure signatures at ground level for small, medium, and large aircraft in steady level flight. (Data from ref. 2.)

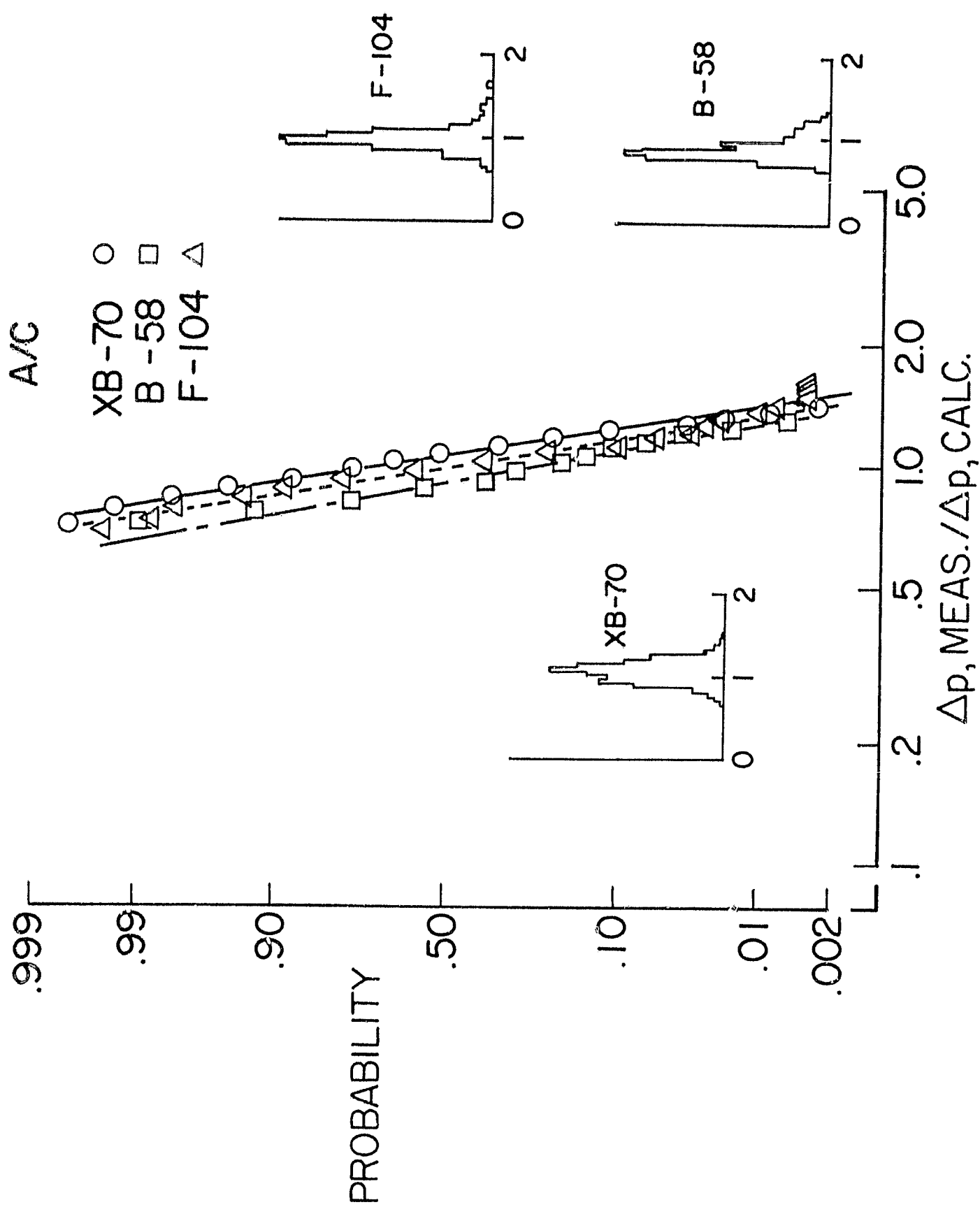


Figure 5.- Probability of equaling or exceeding given values of the ratio of measured to calculated sonic boom overpressures for three different aircraft. (Data from ref. 4.)

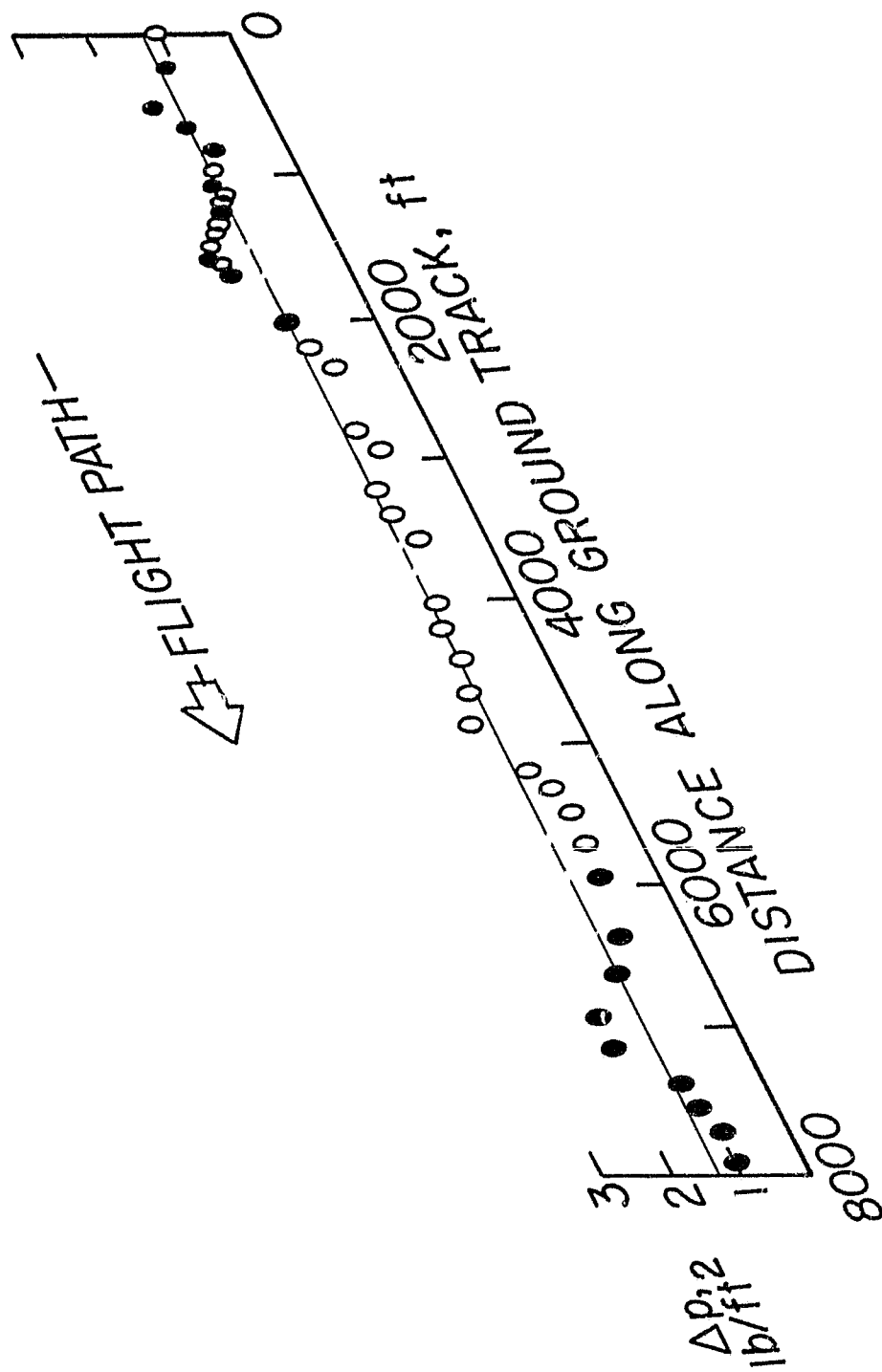


Figure 6.- Sonic boom overpressures as a function of distance along the ground track.  
(Data from ref. 5.)



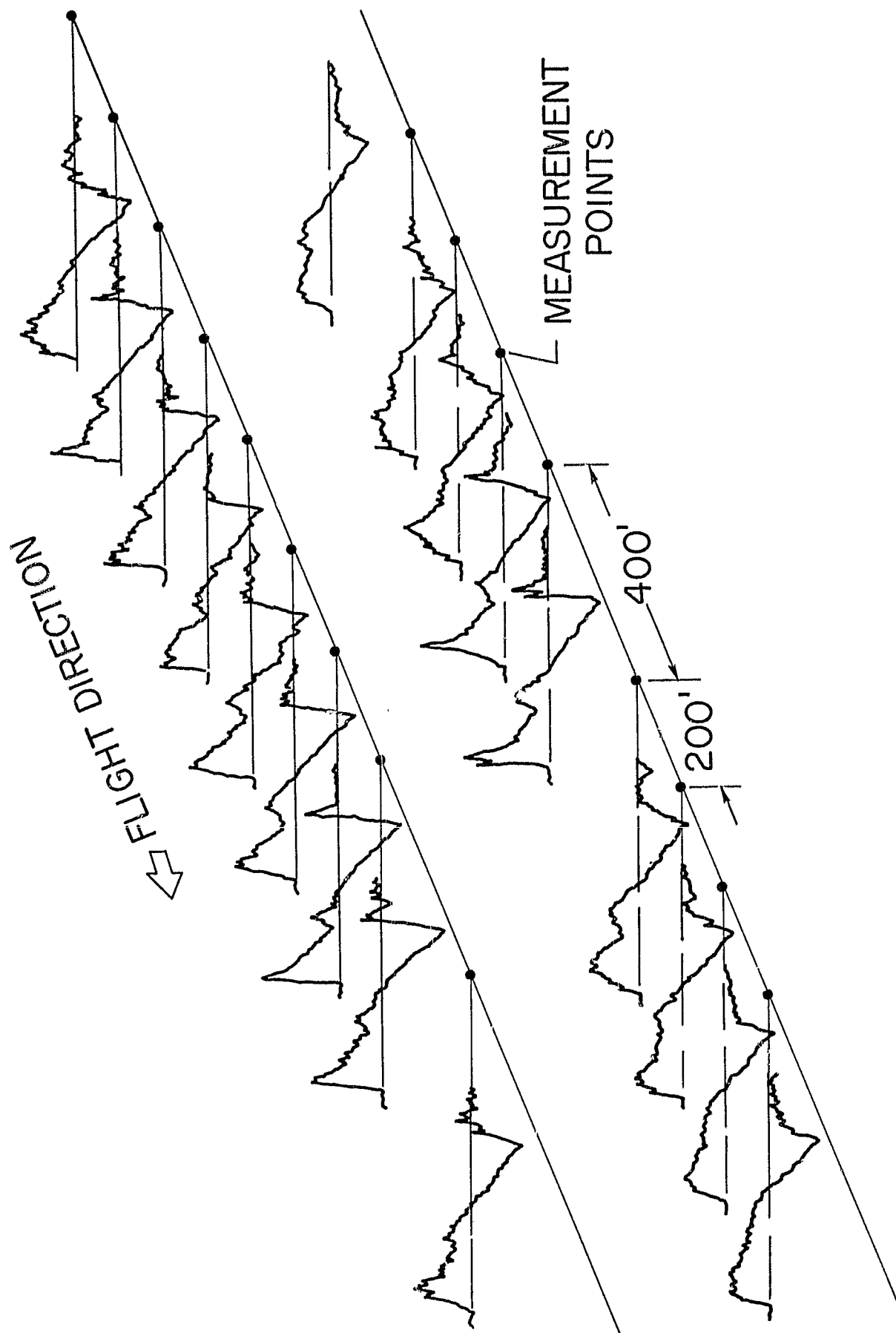


Figure 7.- Tracings of sonic boom signatures recorded at several points 200 feet apart along the ground track. (Data from ref. 5.)

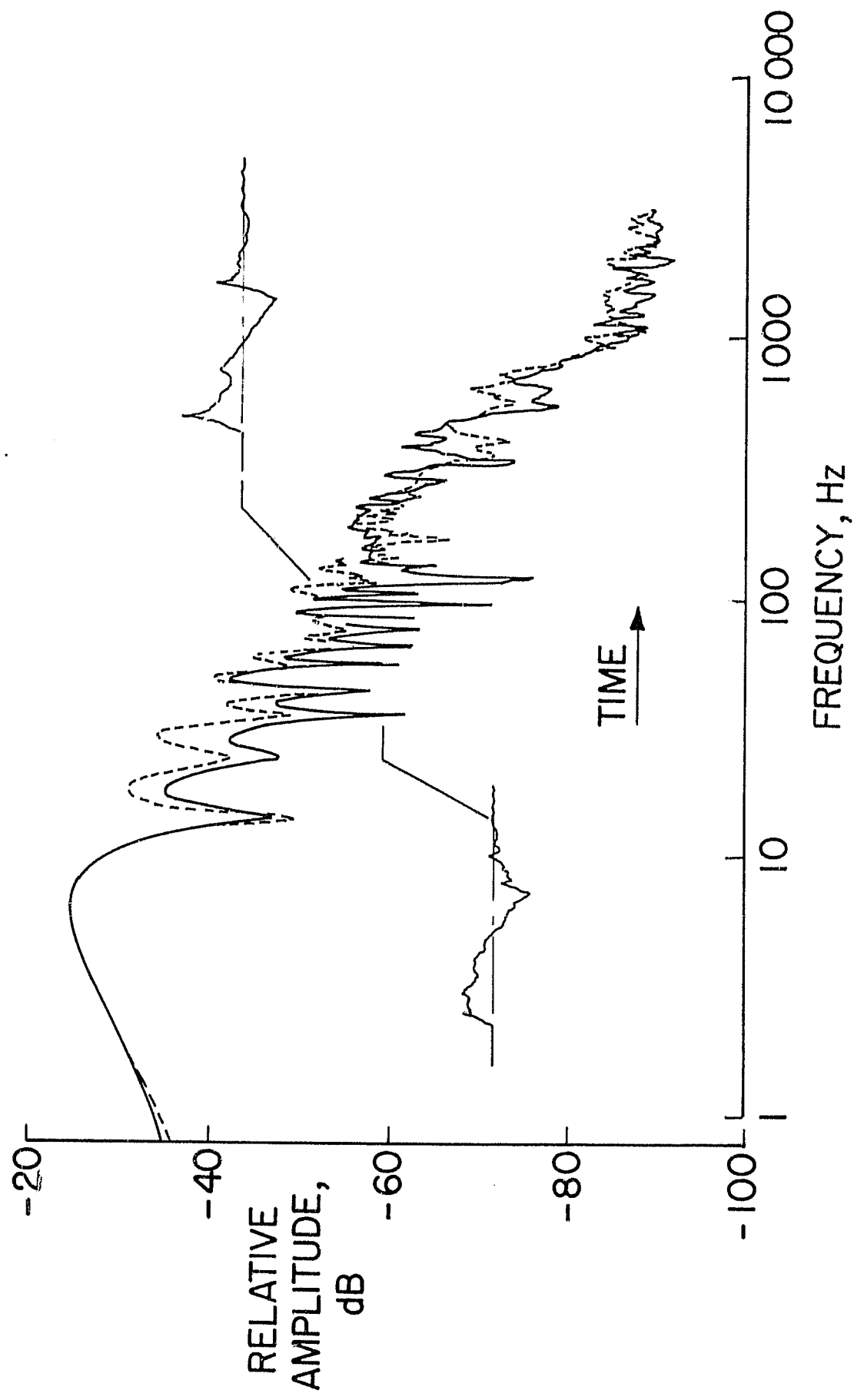


Figure 8.- Energy spectra for two different shapes of sonic boom signatures. (Data from ref. 4.)

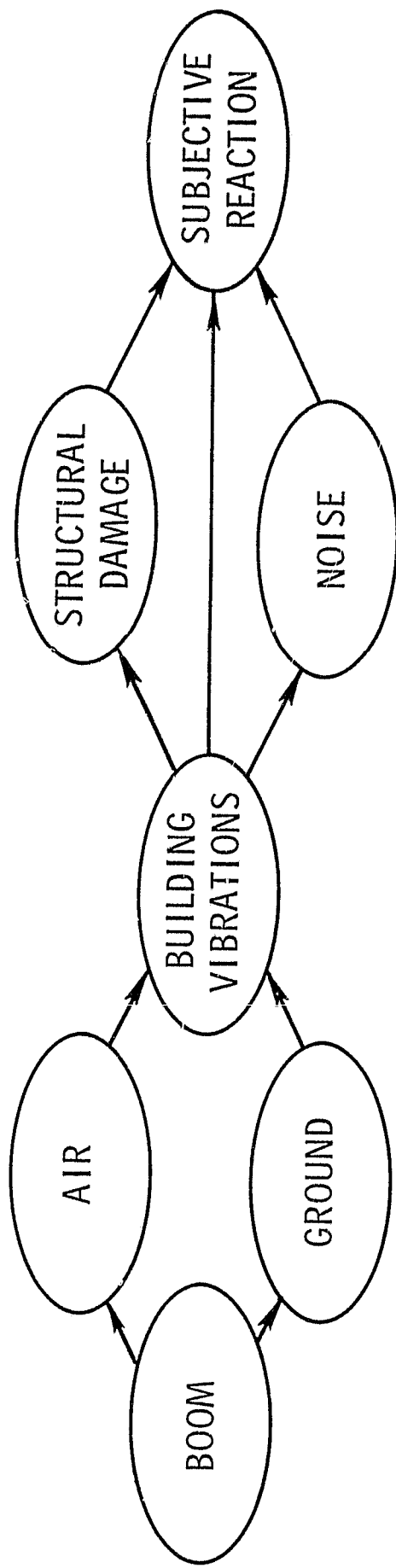
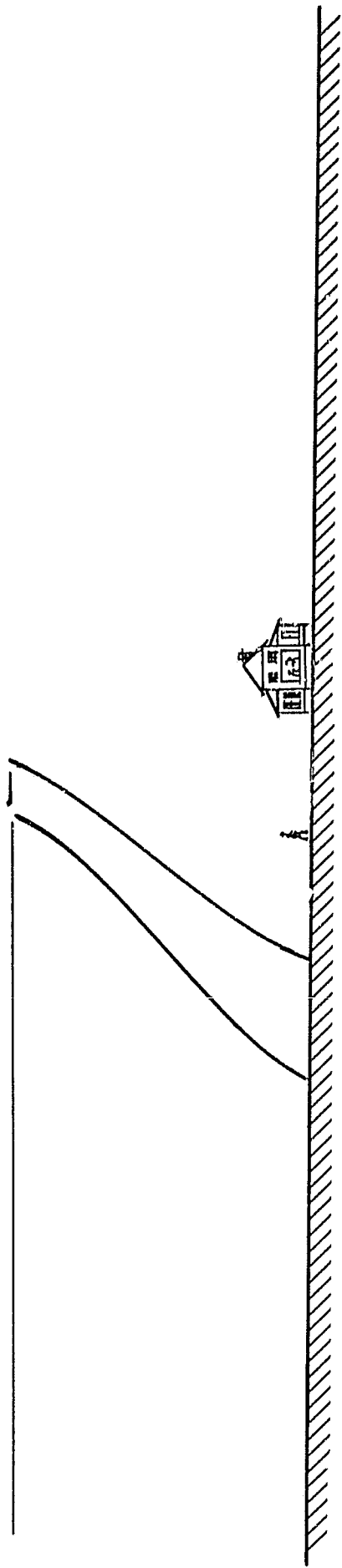


Figure 9.- Factors involved in sonic boom exposures. (Data from ref. 6.)

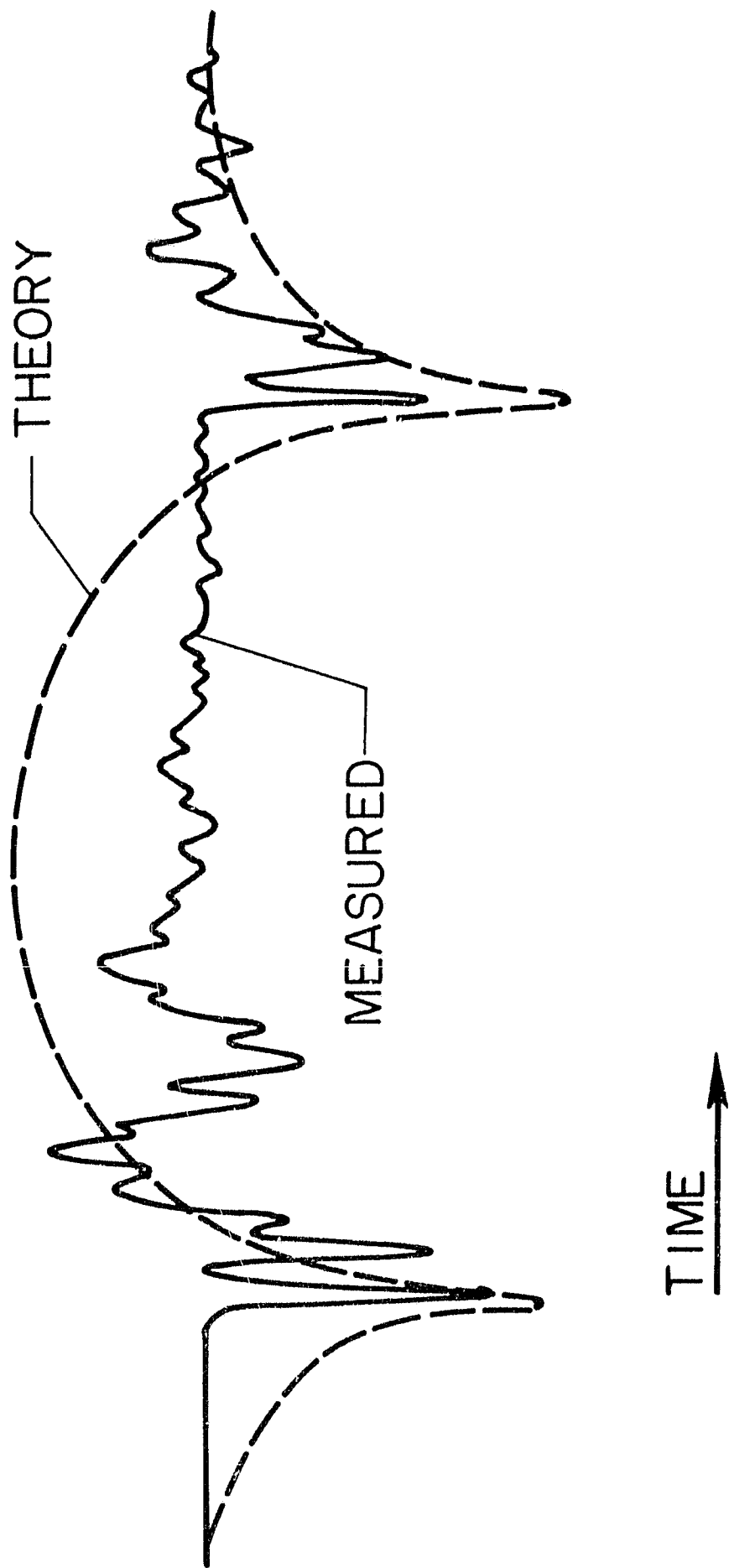
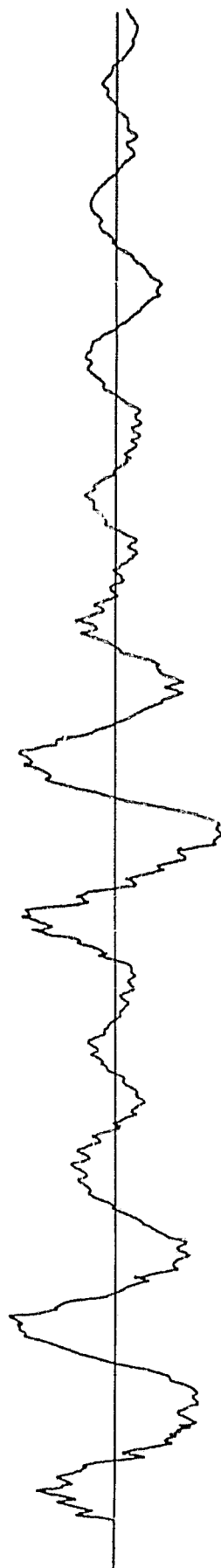


Figure 10.- Comparison of measured and calculated sonic boom induced particle velocities  
in the ground. (Data from ref. 7.)

0.10 sec



B-58 SONIC BOOM



KC-135 ENGINE NOISE

Figure 11.- Sample acceleration response time histories for a residence-type structure as a result of exposure to a sonic boom and to engine noise. (Data from ref. 2.)



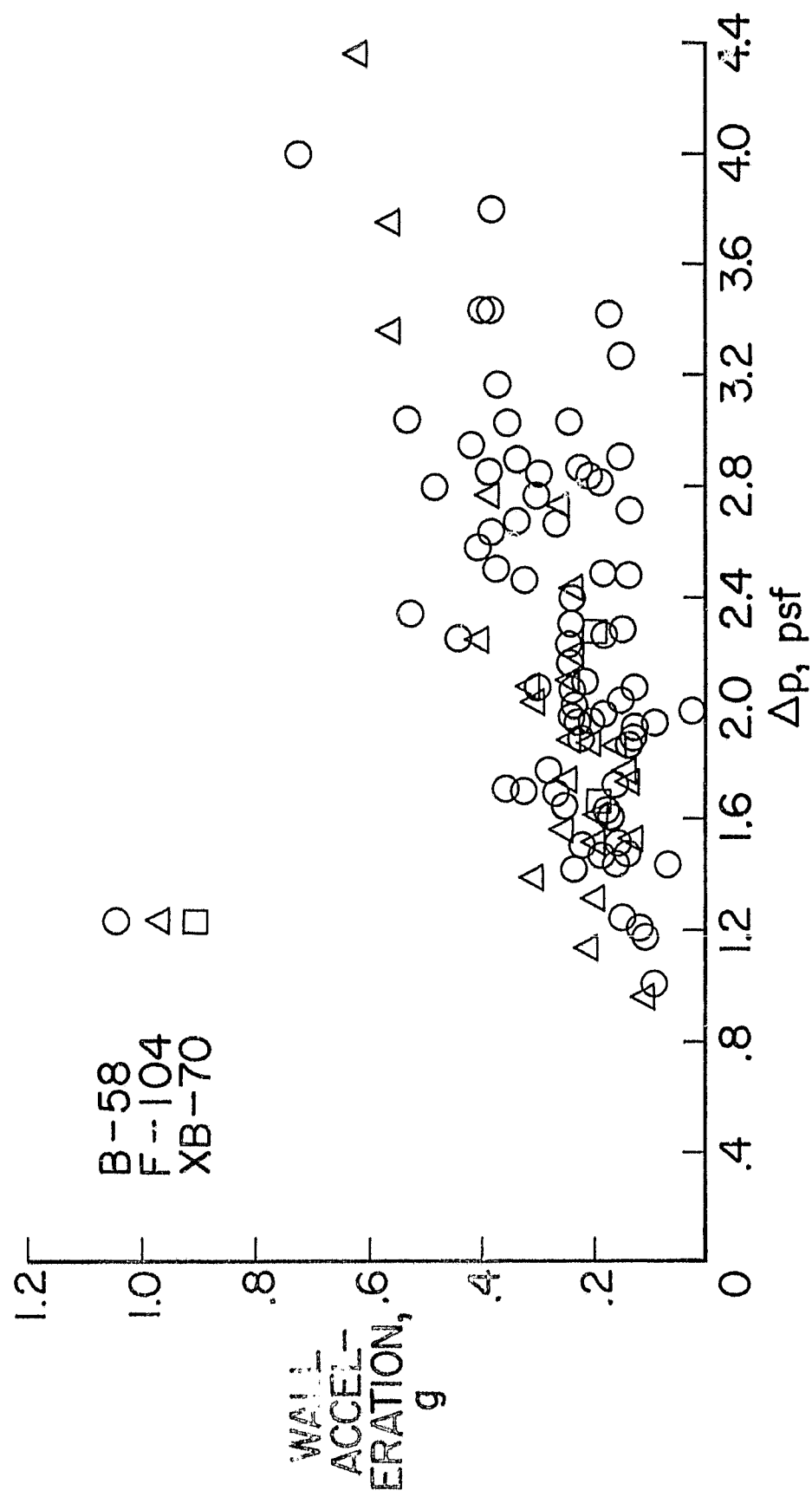


Figure 12.- Maximum building wall acceleration amplitudes as a function of overpressure for three different airplanes. (Data from ref. 6.)

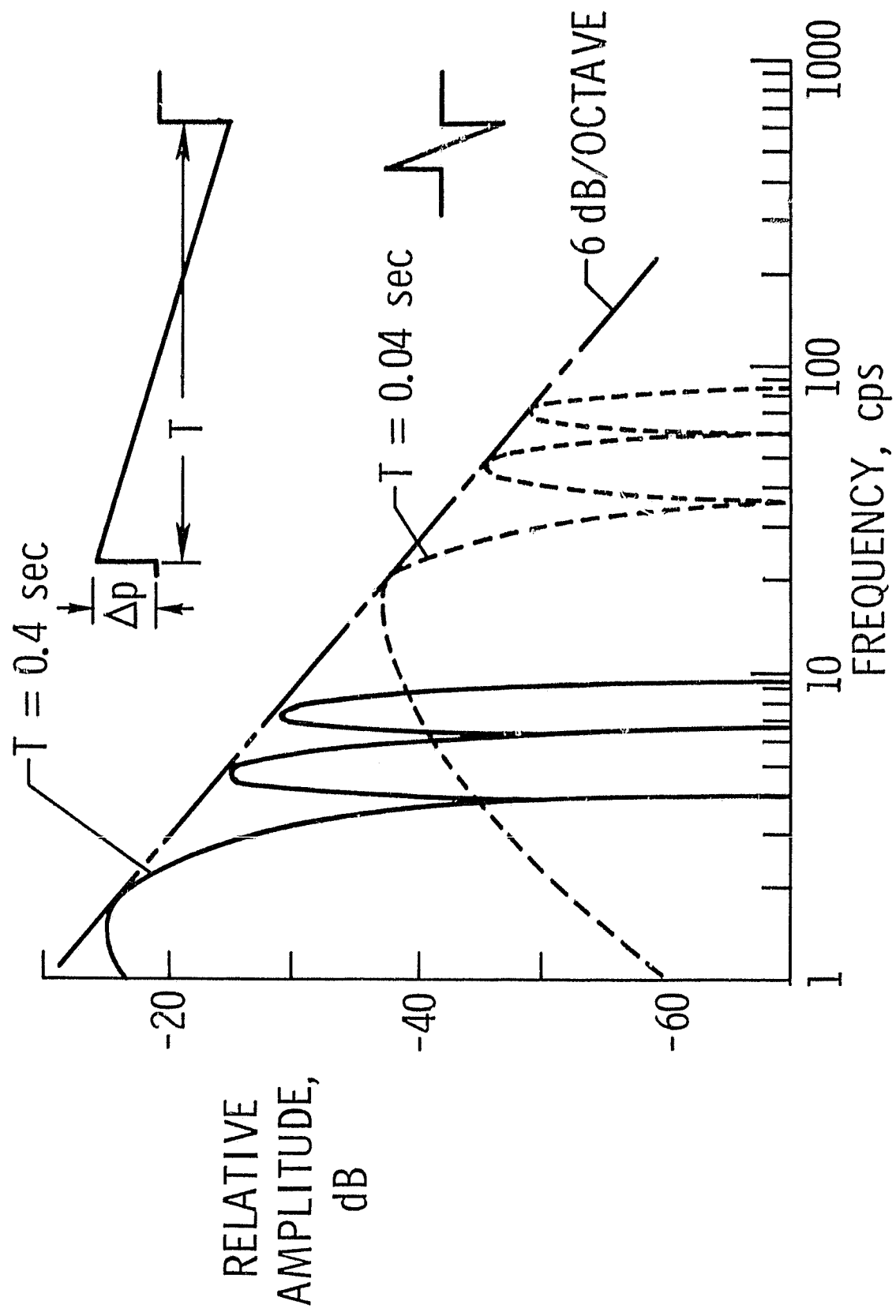


Figure 13.- Schematic illustrations of the energy spectra of N-waves having equal overpressures but two different time duration values. (Data from ref. 6.)

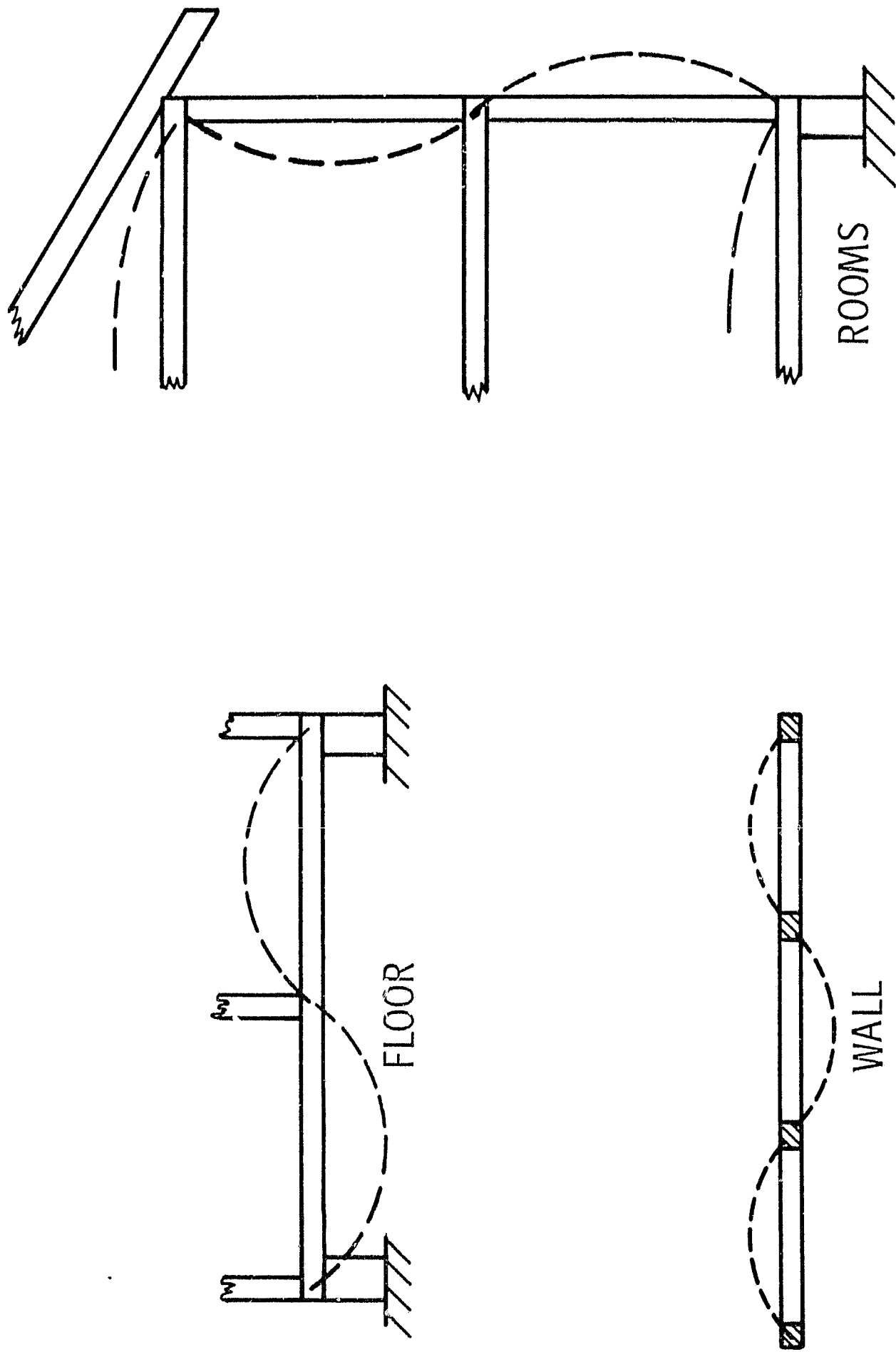


Figure 14.- Measured modal responses for a two-story residence-type structure.  
(Data from ref. 6.)

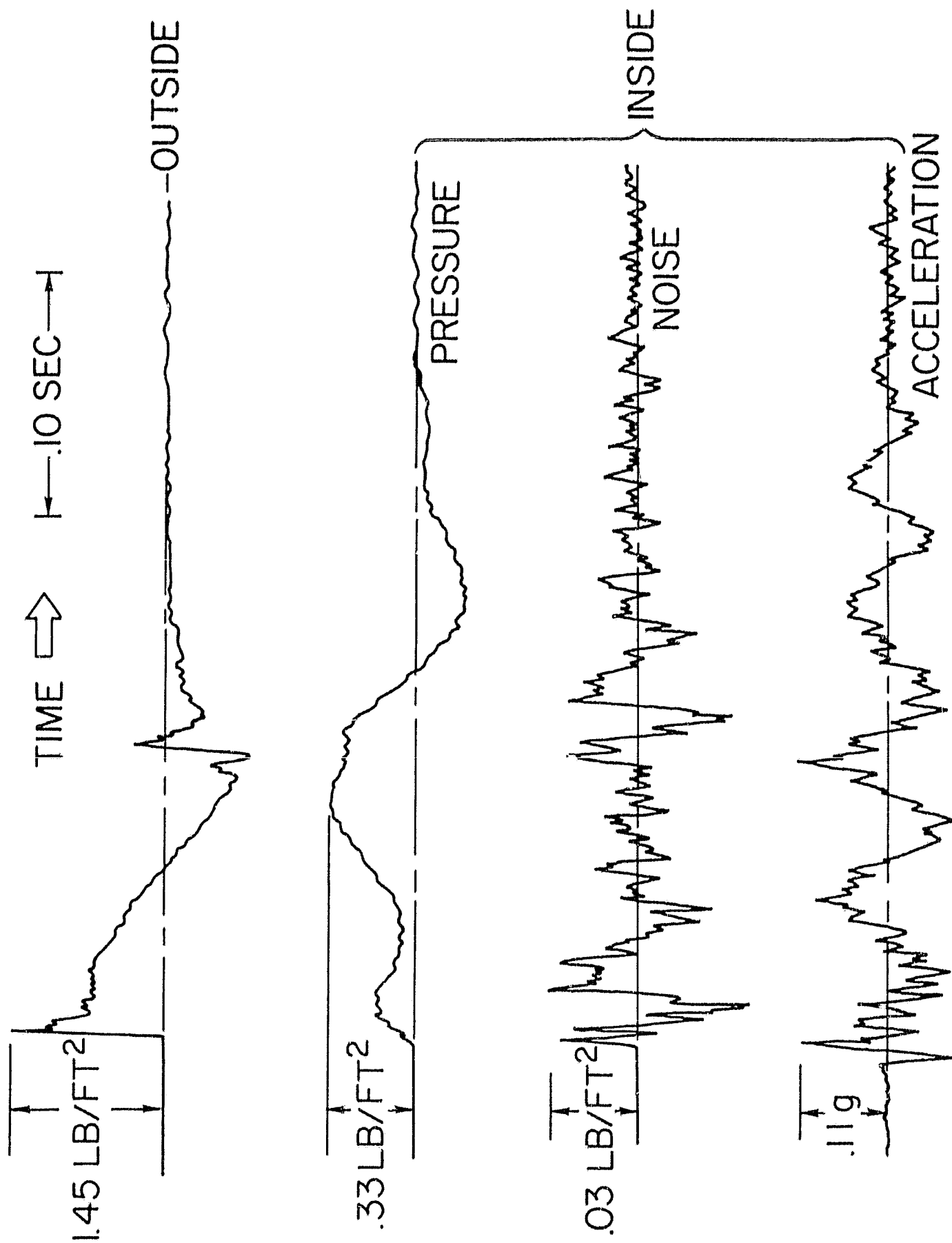


Figure 15.- Outside and inside exposure stimuli due to sonic booms. (Data from ref. 3.)

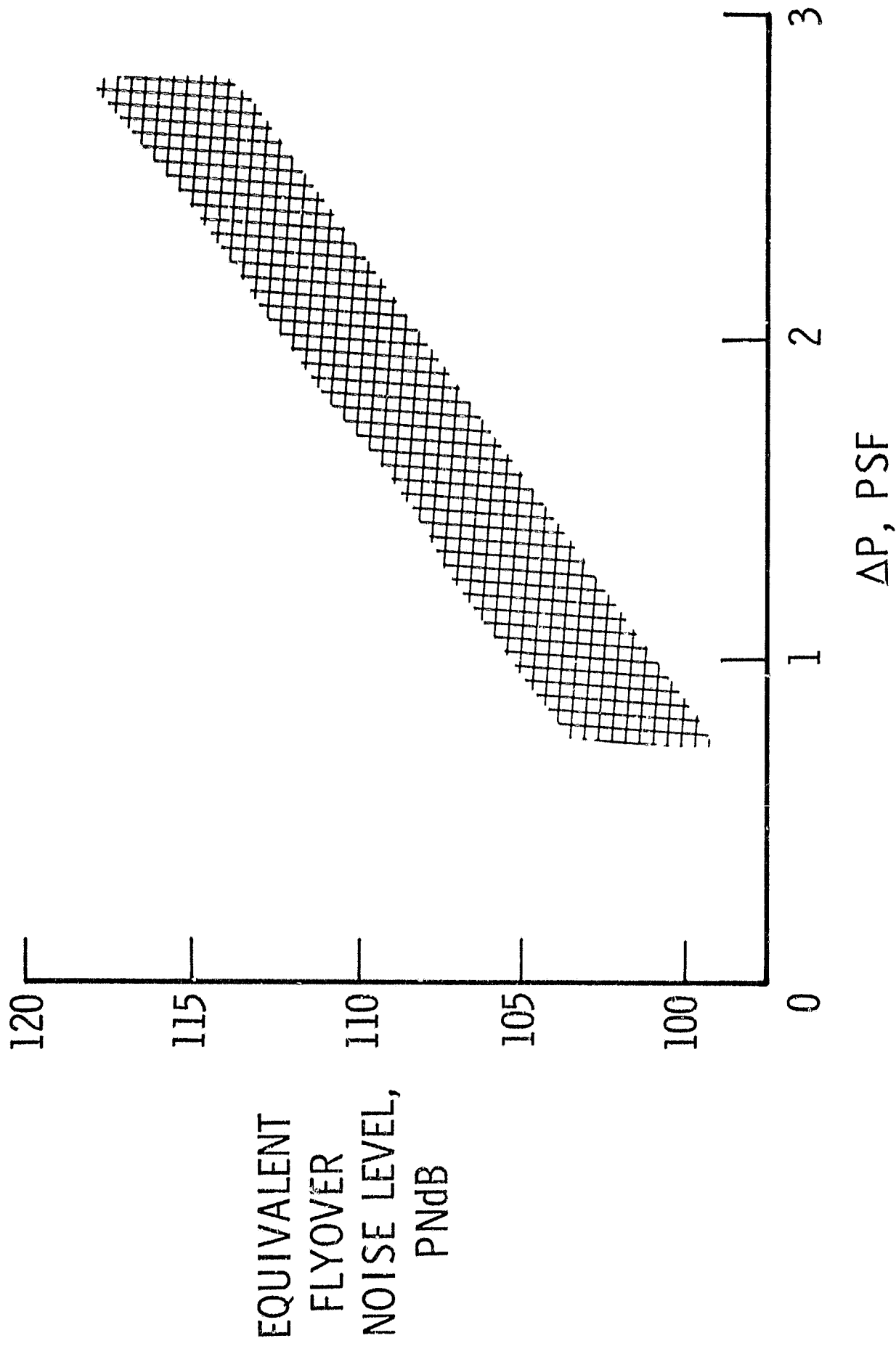


Figure 16.- Acceptability equivalence of sonic boom overpressures and aircraft flyover noise levels. (Data from ref. 2.)



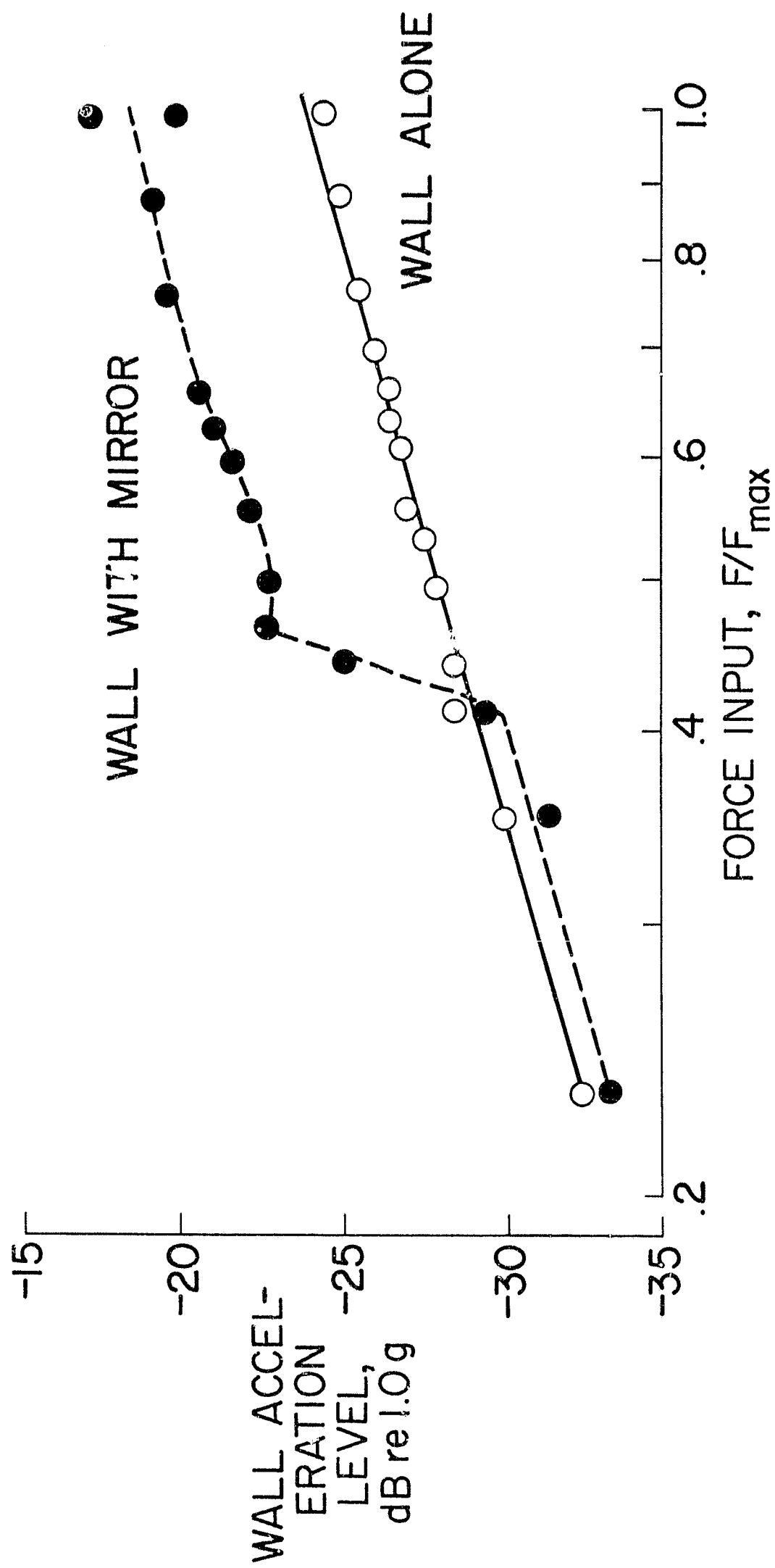


Figure 17.- Measured acceleration levels as a function of force input for wall with and without mirror. (Rattling of mirror is associated with high levels, data from ref. 8.)

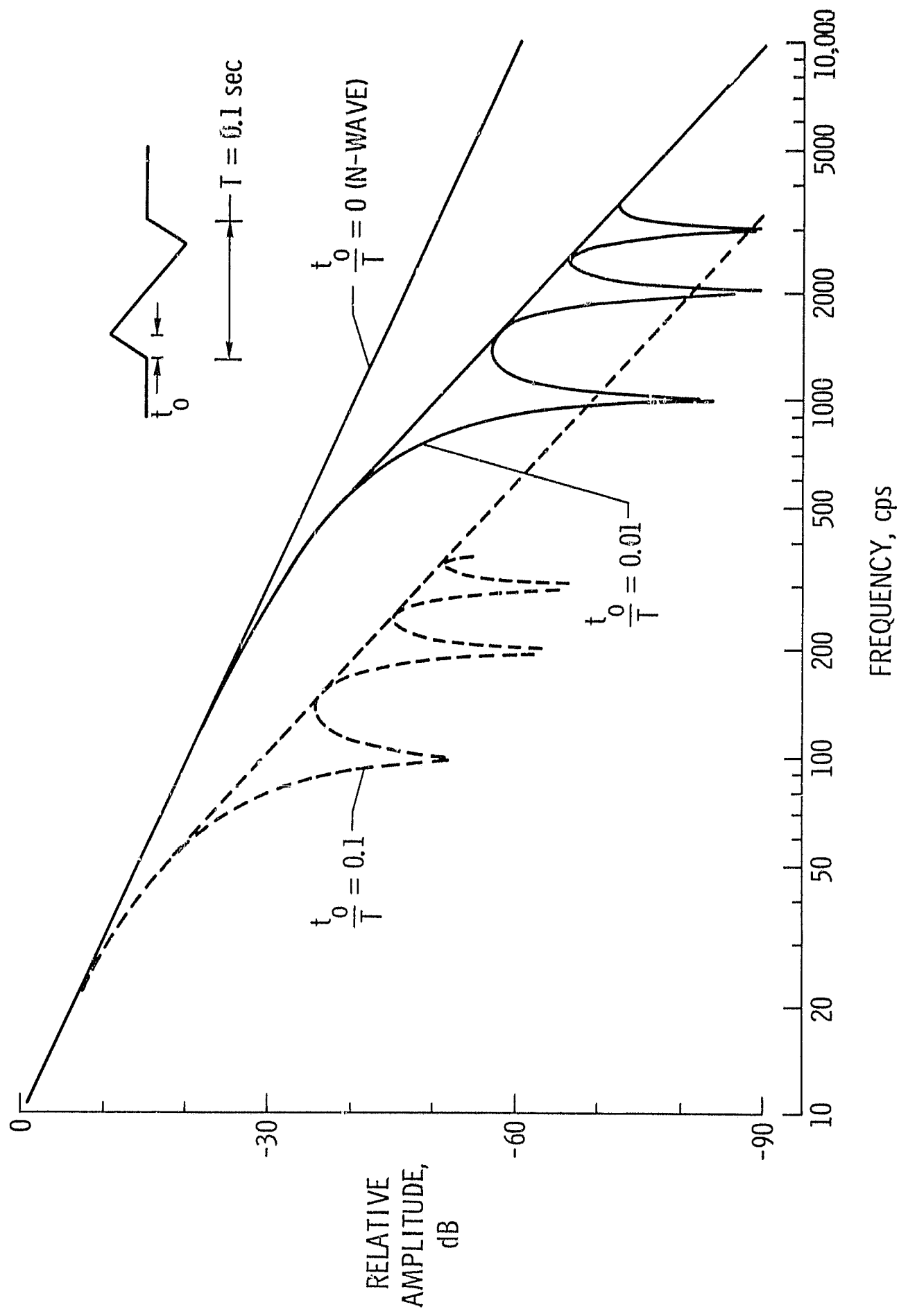


Figure 18.- Effects of rise time on the energy spectra of N-waves having the same time duration.  
(Data from ref. 6.)

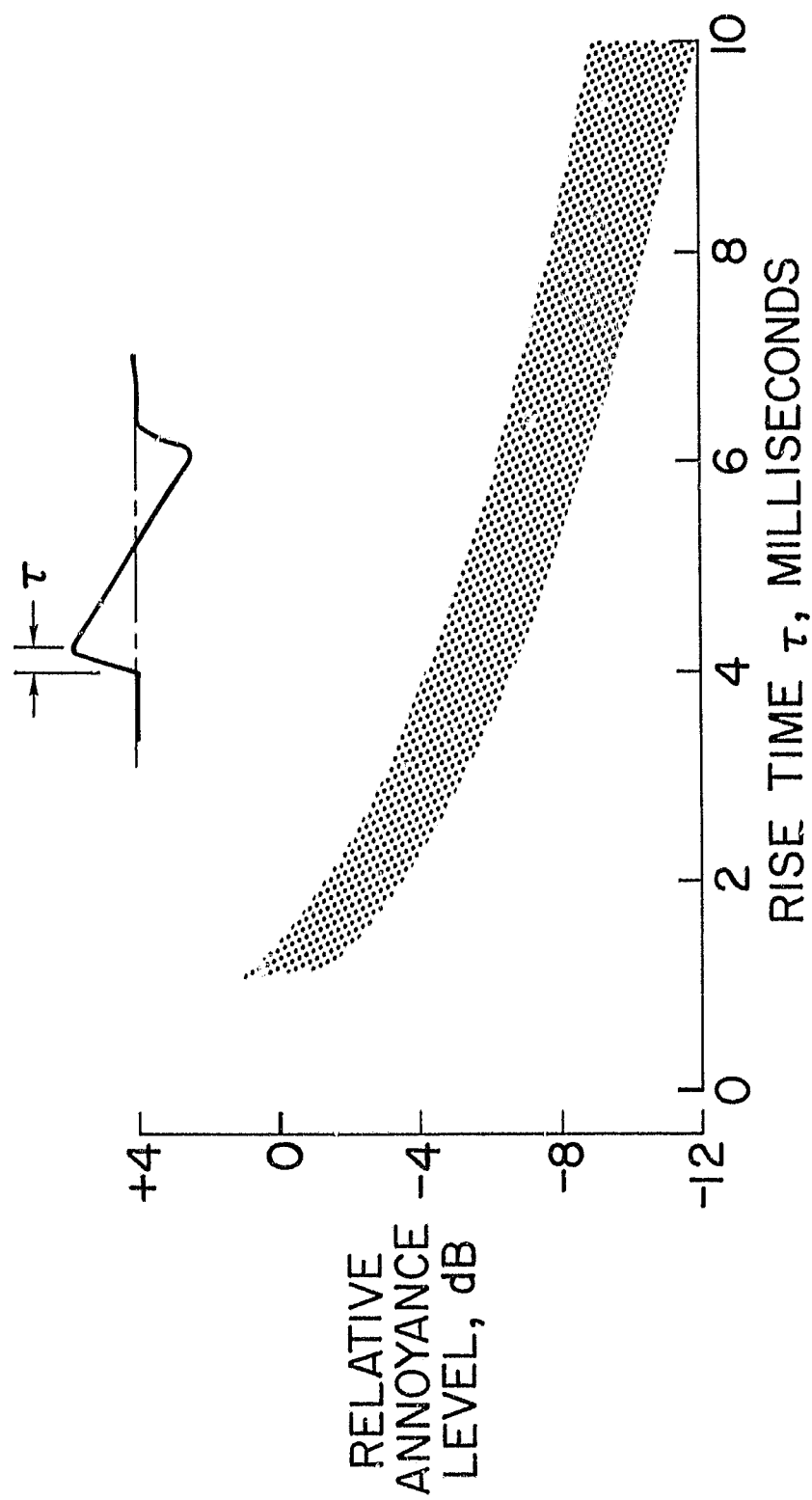


Figure 19.- Relative annoyance level of N-type waves as a function of rise time.  
(Data from ref. 9.)